Chapter 7
Satellite Images for Modeling Terrain Instability in Saudi Arabia (Jeddah-Rabigh)

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Abstract Natural hazards became the foremost geo-environmental issue in several regions worldwide. Rarely a month goes by without a disastrous event that impacts urbanism and environment. The influence of natural hazards is being increased due to the development of many physical and man-made influencers. These hazards imply many types and occur with different dimensions. Due to its complicated geology and geomorphology, the Kingdom of Saudi Arabia encompasses a miscellany of disasters of the natural origin, and terrain instability is one of the influencing types where it occupies tremendous localities including urban and rural ones. It usually impacts many communities and plays a role in the socioeconomic changes. The increased number of events related to terrain instability makes it necessary to elaborate relevant studies. Therefore, mapping instable terrain has become urgent and must be accounted in many projects. The use of satellite images proved to be significant tool for modeling different factors controlling the existence of terrain instability. This chapter will illustrate these factors, as thematic layers, which have been extracted and manipulated by satellite images processing and GIS systems. Results show that about 89% of the area between Jeddah and Rabigh is under terrain instability risk (ranges from high to very high risk).

Keywords Mass movement · Damages · Slope · DEM · Spot images

7.1 Types of Terrain Instability

Terrain instability is a geo-environmental issue, especially where urbanism is increasing. It is usually interlinked with the term "Mass Movement" which expresses the movement of different terrain materials (rock and soil) by the effect of physical forces (e.g. water. Slope, wind, etc.) and in some cases by the influence of human activities such as: excavation, construction, etc. Thus, mass movement follows

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diverse mechanisms and resulted severe damages and destruction, which might be harmful to human and nature. Thus, it is necessary to investigate the stability of terrain where new construction projects, transportation systems, planned settlements, etc. will take place.

Slopes are most hazardous terrain surfaces, notably when unconsolidated materials are located. It is a widespread risk occurs in many localities of the Kingdom of Saudi Arabia. In this regard, several studies and projects are applied on natural risk, aiming to reduce and mitigate its impact. This is well pronounced on slopes, certainly along the descents between the Arabian Shield and the Red Sea coast. Therefore, many rock deformations exist such as escarpments, faulting, rock toppling, etc. and then create slope instability and rock fall and sliding, especially after rain storms (Al Saud, 2018).

Three major types of the instability of terrain exist the Kingdom of Saudi Arabia where they are viewed from the hazardous point of view. The first two are interlinked with materials mobility along slopes (i.e. landslides and rock falls); while the third one is often with limited and local movement and then represents either land subsidence or uplift.

7.1.1 Landslides

Landslides represent one of the well-known natural hazards occur in many regions where they might be at small and large scale. Thus, the degree of damage results from landslides is mainly controlled by its dimension and the mechanism of movement. However, a large landslide are always resulted in severe damages in the environment and human and it is considered as a risky threat and this is exactly the case in the Kingdom of Saudi Arabia.

Landslides are described as rocks, soil, or debris flows (sliding) by the impact of gravity along slopes. They represent the movement of surficial materials along terrain where a direct contact between these materials and terrain remain from the beginning of movement until these materials settle down. While, the duration of landslide movement ranges from very slow to very rapid, and it exists on any terrain given the suitable conditions of soil, moisture, and the angle of slope. Integral to the natural process of the earth's surface geology, landslides serve to redistribute soil and sediments in a process that can be in sudden collapses or in slow gradual slides (Al Saud, 2018).

There are many factors controlling the occurrence of landslides. These factors implies the geologic, morphological, meteorological and man-made origin. Thus, some factors can act separately in creating terrain instability, while sometime two or more of them act together. Hence, landslides might be triggered by torrential rain, floods, earthquake and other causes obtained by human intervention, such as excavation, terrain cutting and filling, etc.

There are many features characterize the type of landslides, with a special emphasis to: rotational, translational, debris flow and avalanche, earth flow, creeping

Table 7.1 Major types of landslides (Varnes, 1978)

Type of landslide	Bed rock	Engineering soils	
		Predominantly coarse	Predominantly fine
Rotational	Rock slide	Debris slide	Earth slide
Translational			
Lateral spread	Rock spread	Debris spread	Earth spread
Flows	Rock flow	Debris flow	Earth flow
	Creep	Soil creep	
Complex	Combination of two or more types of movement		

Fig. 7.1 Rocks susceptible to roll towards the road. (Al Saud, 2018)

and lateral spread. According to Varnes (1978), landslides were interlinked to their rock type and the engineering soils as in Table 7.1.

7.1.2 *Rock Falls*

Another aspect of mass movement, rock fall is a common risky phenomenon. However, rock fall (or sometimes called mass wasting) differs from landslide in that it is attributed to the movement of materials on air, whereas a landslide moves (or intermittently) on terrain surface. These can be as rock crumpling, toppling and rolling (example in Fig. 7.1). Thus, the movement mechanism of surface materials belongs to rock fall is characterized by fast process.

For rock fall, factors controlling the mechanism of movement are almost similar to those for landslides, but the type of surface materials in this case are mainly of hard and consolidated rocks with different size ranging between gravel and debris to rock boulders and masses.

Normally, free rock fall typically happens along slopes steeper than 76°, bouncing on slopes between 45 and 76°, and rolling on slopes less than 45°. However, a rock may alternate between the three modes during its downslope movement, because slopes are often irregular (Al Saud, 2018).

The dimension of event resulted from fallen rocks, as mass wasting, is mainly governed by thickness of **rock bed**s, joint sets and the existing fractures systems which act in the fragmentation of rocks, and then detach the fragmented and collapsed rocks long the slope. In addition, the length of fissures and the volume of fallen rocks, tend to follow power law or fractal distributions, meaning that their numbers decrease exponentially as fracture length and rock fall volume increases.

7.1.3 Subsidence and Uplifts

This type of terrain instability is well known in many regions, likewise in the Kingdom of Saudi Arabia (Fig. 7.2). It is often has a minimal movement of surface materials if compared with landslides and rock fall. This type of terrain instability includes the pull-down (i.e. subsidence) or the pull-up (i.e. uplift) of the terrain surface. These movements are usually accompanied with ground fissuring and cracking whether in soil or in rocks, and the associated subsidence or uplift, which occur in the middle part of the subsided or uplifted locality.

The resulting fissures associated with the subsidence or uplift of the ground surface, often ranging from a small-scale cracks to large faults; where they begin as small traces that expand later on due to the external factors such as erosion and

Fig. 7.2 Land subsidence near Jeddah area

rainfall. Sometimes this type of fissures are caused by the change in the soil nature, especially along the sides of the basins due to the presence of rugged rock topography underneath these soil layers (Budetta, 2004). Moreover, ground cracks can evenly begin at great depths below the surface, as a result of horizontal movement in the aquifers due to excessive withdrawal of the ground water from the fragmented-rock reservoirs, also due to loess soil, and earthquakes. These fissures and subsidence could cause many problems in the urbanized and agricultural areas and induce damages to the infrastructure. (Holzer, 1984).

Under arid conditions such as in desert areas, the shortage of groundwater resources leads to excessive pumping that may aggravate land subsidence incidents. This is the case in many areas in the Kingdom of Saudi Arabia they suffer from groundwater overexploitation resulting in land subsidence and fissuring which also lead to damage of agricultural areas due to loss of water and sometimes injuries from the hidden fissures. (Bankher, 1996).

Terrain uplift is also a widespread phenomenon, but it has different mechanism than subsidence in term of movement direction, and it is mainly originated as a result of tectonic activities and the related rocks deformation. Furthermore, earthquakes can cause ground movement through cracking which may span for long distances. In addition, delta sediments that are saturated with water and Sabkhas are the suitable localities that could be affected by subsidence and fissures or faulting due to earthquakes. Examples on faulting and fissuring, that lead to subsidence and uplifts in Saudi Arabia and attributed to the earthquake and volcanic activities, occurred in Harrat Lunayyir (east to Younba City), where the movement of magma led to seismic activity, resulting from the rise and subsidence in the terrain surface, causing numerous cracks and faults. (Bankher, 1996).

7.2 Factors Influencing Terrain Instability

There are several physical and anthropogenic factors controlling the stability of terrain. However, these factors differ from one region to another depending on the existing natural and man-made characteristics and intervention which is triggering terrain instability. According to Al Saud (2018), these factors can be summarized as follows:

1. Geology: This includes the characteristics of rock lithology and the existence of weak and weathered, sheared and fissured surficial materials, plus rock layer discontinuity and many other features of rock deformation and lithological friability.
2. Geomorphology: This encompasses tremendous morphological features and processes that act in disintegrating and weakening the terrain material, such as: deposition loading slope, thawing, freezing alluvial and glacier erosion.

   Meteorology: Meteorological impact on terrain instability and other natural hazards is well pronounced, where it plays from the accumulated and running water due to torrential rainfall for example, as well as the increased temperature and its impact on the shrinking of the surficial materials, and then losing their consolidation. In addition, there are several meteorological parameters that may play a role in terrain instability, such as wind, heat waves, freezing, etc.; as well as the abrupt changes in climatic conditions has a significant role.

3. Human interference: In many cases human works (e.g. excavation, dumping, mining, artificial vibration, etc.) act in the enhancement of ground fragility and then accelerating mass movements from their original place. This interference differ between regions and over different time periods.

Classification of factors influencing terrain stability are often different between researchers, but all accorded that these factors are resulted in damages which might be severe in some cases. For example, an acute tectonic seismicity can result the movement of rock and soil masses where other factor, such the geomorphology including mainly the slope, can also control the mechanism of any movement. Moreover, climatic extremes results detaching of surface materials and then enhance transportation processes.

According to the physical setting of the Kingdom of Saudi Arabia, factors affecting the occurrence of terrain instability are many, even though they differ between the Saudi regions. However, each region encompasses a number factors that might not exist in other regions. Thus, the study area is located between Jeddah and Rabigh (19,723 km^2), is a representative region where it is characterized by mountain ridges and coastal plain along the western Saudi coast. Therefore, the most influencing factors on terrain instability in the area of study were primarily determined. This has been done using many tools including satellite images analysis and field surveys, as well as, records and datasets from previous studies. In this regards, the use of space techniques was the most significant tool in this study notably in identifying instable localities. In addition, geological maps were used as supportive tool. Therefore, the following factors were adopted for investigating instable terrain in the area of study (Al Saud, 2018).

1. Slope: The inclination of topographic surfaces is has high gravitational impact on moving objects on these surfaces. Thus, when slope angle exceeds, soil and rock masses will move either slowly or suddenly following different mechanisms along the slope surface. In this regard, there are many elements controlling the timing of slope failure and its mechanism, and this includes, in addition to the slope angle, hardness of the objects located along the slope and surface roughness.

More than one parameter play together in moving terrain materials along slopes. However, the angle of friction can be separately able to move surface materials since it represents the maximum angle for slope-tolerant holding objects. Hence, the area of study is known by the flat terrain surface at the coastal plain, besides a sloping terrain at the adjacent mountain chains located to the east, and thus, tremendous slopes exist.

Al Saud (2012, 2018), classified terrain instability, as viewed from the morphological setting and field observations in the study area, as follows:

- Sudden movement and hazardous location at high slopes,
- Rapid movement and instable terrain at slight high slopes,
- Instable terrain exists when more than one parameter exists at moderate slopes,
- Difficult movement along terrain (almost stable) at slight low slopes,
- No remarkable movement at very low slopes.

2. Lithological characteristics: This lithological feature is one of the major factors that affecting terrain stability. It reflects the consolidation of rocks either as hard rock lithology or soft ones. These characteristics are controlled by the physical properties of rocks, such as the porosity, permeability, grain sorting, etc.

Normally, soft lithologies are susceptible to move than hard ones, but the latter might exist if more factors act. For example, hard limestone rocks are often stable, but when fractures occur among, surfaces of weakness will be developed between the bedding planes and result terrain instability.The area between Jeddah and Rabigh is known by numerous types of rock lithologies. This occupies the three major rock types (i.e. sedimentary, igneous and metamorphic) with diverse features of rock stratification and deformation. Therefore, five classes were considered for the lithological characterization with respect to terrain instability. This classification has been viewed from rock rigidity. According to Al Saud (2018), these classes are:

- All igneous and metamorphic rocks – very stable
- Carbonates facies – slightly stable
- Sandstone and other clastic rocks – non-compacted
- Alluvial and talus deposits and saline muds – instable
- Aeolian sediments and dunes – movable.

3. Fractures: This type of rock deformation is utmost significant in terrain instability and occurs at different scale and shapes. They can be as fault alignments with long distances or as local fissure systems with few centimetres. It is often considered as the primary factor in rock instability, since fractures increase rock fragmentation and friability. However, this factor is also related to/or originated from acting physical forces and specifically the tectonic activities. Therefore, terrain surface with dens fracture systems, including fissures and joints, are often instable.

   The area between Jeddah and Rabigh is characterized by dense fractures due to the complicated tectonic setting, especially it is located in the proximity of the Arabian Shield which is almost surrounded the eastern side of the study area. Therefore, the obtained classification of fractures according to terrain instability depended mainly on the number of fracture density (a function of number of fractures in a define area). Hence, zones with dense fractures are considered as unstable and vice versa. Based on this concept; however, five classes of fracture density were adopted in this study.

Landforms: A landform is characterized by the belonging physical attributes such as slope, elevation, orientation, rock and soil type, soil type, and rock exposure. This sometimes represented by land cover which describes a number of terrain features and topographic aspects. Thus, landforms in the area of study constitute a number of terrain surfaces and orientations. Therefore, the physical properties of the mentioned landforms govern the stability of terrain, and more certainly lithological characteristics and slope degree, which are in direct relationship with soil and rock types in the area of study. In this regards, Al Saud (2018), classified landforms in the area of study as: slopping surfaces as the most vulnerable to instability, and this should be integrated with lithological characteristics where soft rocks and soil exist. Besides, flat surfaces with hard terrain materials would be much stable.

7.3 Tools for Analysis

Perhaps the identification of factors influencing terrain instability should be primarily determined, and then they should be digitally mapped for the entire area between Jeddah and Rabigh. This requires using different tools and techniques for data retrieve, extraction and manipulation. This implies advanced techniques to elaborate and analyze geospatial data required.

The availability of tools required is a significant element. They also need skilled expertise. Table 7.2 shows the tools and techniques used for investigating the influencing factors on different types of terrain instability in the area of study.

The concept behind the applied method includes mainly the preparation of data on the influencing factors, and each factor was treated separately (Fig. 7.3). Hence, the major factors influencing terrain instability (i.e. slope, lithology, fractures and landforms) were treated. Each factor has a number of elements reflecting the effect on terrain instability. Some elements act towards increasing terrain instability while other elements work in opposite direction, and this must be restrictedly identified. Thus, each factors will be classified into 5 classes according to terrain instability, and therefore, these classes will be systematically integrated in the GIS system (Arcmap) in order to establish the final terrain instability map (Fig. 7.3).

The classes of terrain instability indicate relative ranking of the likelihood of terrain instability that occurs after any natural or anthropogenic event. However, they do not indicate of the level of the expected impact of terrain instability or potential damage. The 5-class terrain instability classification, as shown in this study, is to flag on the potential risk areas. Hence, it should not be understood as an onsite description for terrain stability field assessments.

Table 7.2 Major tools used for studying terrain stability (Al Saud, 2018)

Theme	Tool	Details	Data and information
Documentation	Previous studies and records	Documents and indicative maps	Recognize the available and obtained data and information to support knowledge.
Thematic maps	Geologic maps	Scale 1:250000, Skiba et al., 1986	Identify the geographic distribution of different lithologies and structures.
	Landforms maps	Land resources map, scale 1: 500.000, Ministry of Agriculture and Water, 1986	Determining the geographic distribution of different landforms.
Fracture systems	Satellite images	Geo-Eye-1: 5 bands; 46 cm resolution	Direct identification of observable instable terrain features (landslides, etc.).
		Aster: 14 bands, 15 m resolution (visible bands); 90 m resolution (thermal bands);	Linear thermal anomalies as indicator for fractures systems (i.e. faults).
		Landsat 7 ETM^{+}: 7 bands, 30 m resolution (visible bands); 120 m resolution (thermal bands);	Identify distinguished geologic features needed (e.g. ring structure, domes, etc.).
Slope	SRTM	Radar-based data; 30 m resolution	To extract the digital elevation model (DEM) and slopes
Data manipulation	Software	ERDAS-Imagine-11 (*Leica product*)	Satellite image processing and classification.
		PCI's Geomatica-10.2 (*Geomatica product*)	
		Arc-GIS-10.2 (*Esri product*)	Digital data manipulation and drawing
Filed surveys	Variety of field devices and instruments (e.g. incline-meter, GPS, laser-meter, etc.)		Field verification and inspection.

7.3.1 Slope

Usually, slope maps are generated from topographic maps depending on contour lines. Then, slope calculation can be obtained from these maps when they are digitally produced. Recently, the generation of slope maps is obtained using the geographic information system (GIS) which can be elaborated to build three-dimensional models for any geographic area. Thus, the representation of terrain topography needs require three-dimensions (z, y, x), which is known as digital elevation model (DEM). The applications of DEM became dominant in several applications, specifically in identifying terrain components, such as slope, sunlight exposure, depressions, drainages, etc. (Al Saud, 2012).

Establishing DEMs needs calculating the elevation points whether from digital contour lines or from stereoscopic satellite images (e.g. Spot images). Therefore, Triangulated Irregulated Network (TIN) would be primarily constructed, and they

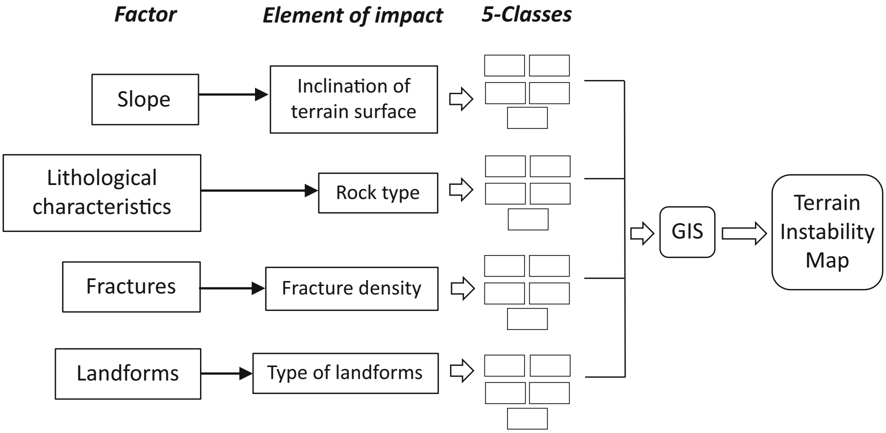

Fig. 7.3 Scheme of elements used in the applied method for mapping terrain stability in Jeddah-Rabigh Region

Table 7.3 Slope classes according to terrain instability in Jeddah-Rabigh Region

Class	Slope description	Terrain instability[a]	Slope Degree[a]	Area (km^2)	%[b]
I	High slope	Moveable	> 35°	3168	16
II	Slightly high slope	Instable	35–25°	2668	13.5
III	Moderately sloping	Non-compacted	25–15°	3072	15.5
IV	Slight low slope	Slightly stable	15–5°	4526	23
V	Low slope	Very stable	<5°	6289	32

[a] According to Fig. 7.4
[b] Percentage of the total studied area

represents digital data structure used in GIS for surface attributes of the natural land surfaces. This will be made up of irregularly distributed nodes and lines with three dimensional coordinates which are arranged in a network of non-overlapping triangles. Therefore, TINs are obtained from mass points, break-lines, and polygons, where they become nodes in the network, and represent primary input into a TIN in order to determine the overall shape of the surface (Al Saud, 2012).

Shuttle Radar Topography Mission (SRTM) was used in this study, to generate DEM. SRTM is a radar-based remote sensing product introduced by NASA. This product is originally made publicly available at a three-arc-second pixel size (1/1200 of a degree of latitude and longitude) with 90 m spatial resolution. In some studies, 90 m pixels are large enough to display the required resolution from SRTM DEM; however, it is now revealed by the much smaller 30 m pixels.

Digital elevation model (DEM) of the study area was generated, and consequently, terrain slopes were extracted and categorized into five classes to illustrate aspects in the area of concern, which will be a used factor while mapping terrain instability. These classes were illustrated in Table 7.3 and mapped Fig. 7.4.

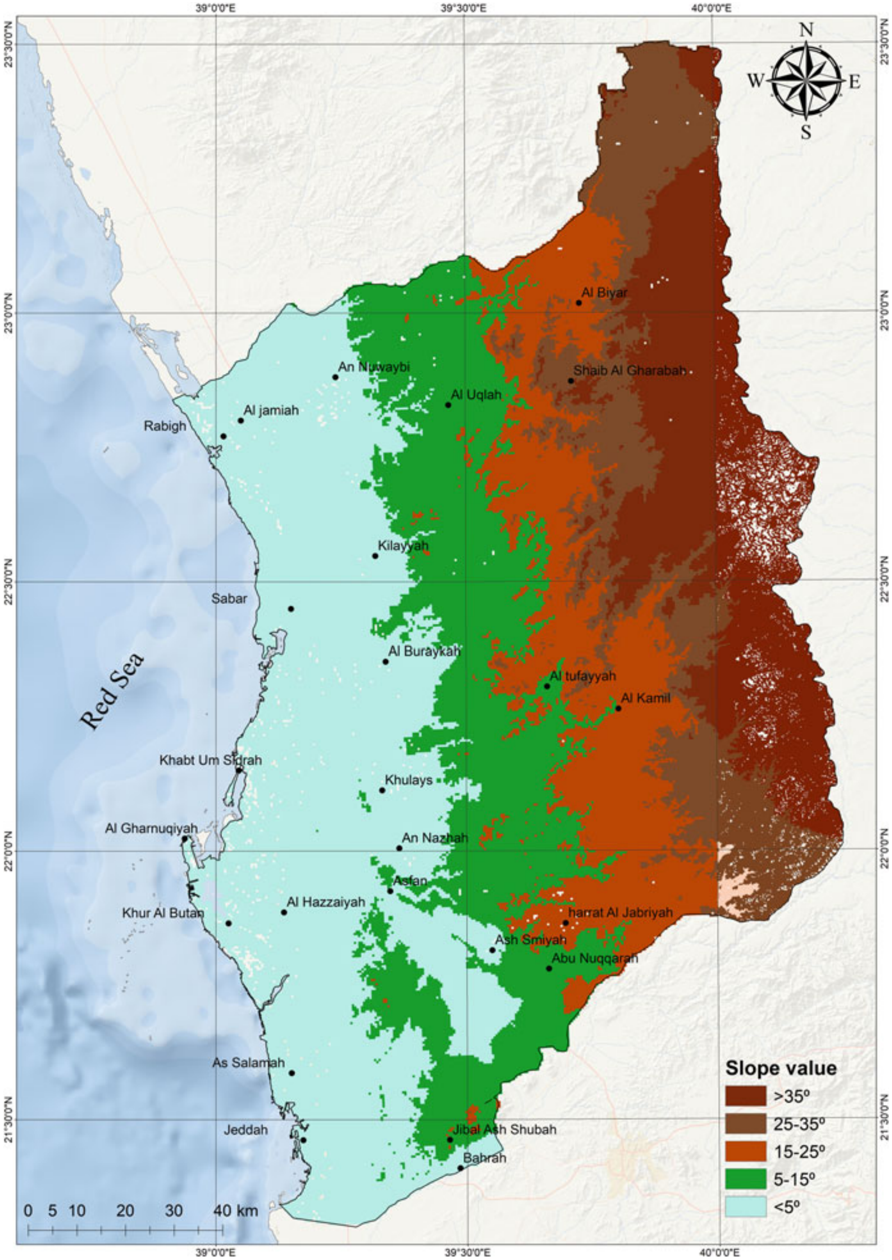

Fig. 7.4 Slope maps of Jeddah-Rabigh Region. (Al Saud, 2018)

7.3.2 Lithology

The geological rock formations in the area between Jeddah and Rabigh were studied and chronologically classified based on geological map done by Al Saud (2018). There 44 geological formations are exposed in the study area and extending from the coast of the Red Sea to the mountains to the east. The oldest geological age of these rock formations is the Precambrian, and they belong to 13 rock groups, suites and complexes.

Almost all rock types with diverse lithologies are exposed in the study area, including the sedimentary, igneous and metamorphic. There is a dominancy for carbonate rocks, silicates, clastic rocks, alluvial and colluvial deposits, intrusive and extrusive igneous rock and lavas, as well as varieties of metamorphosed rocks. The distribution of these lithologies is controlled by the geologic structures, as well as by the geomorphological features, resulting in different bending aspects, unconformable bedding planes, dikes and irregular rock bodies from lava and the igneous and metamorphosed rocks.

Rock formations in the study area have different degrees of impact on terrain instability which is controlled mainly by lithology including the physical and mineralogical characteristics. Therefore, an empirical classification (i.e. categorization of rock types) for the exposed rock formations, was adopted regardless of their age and location. Emphases were on the lithological characteristics and then how to respond to terrain instability in terms of water retention, porosity, permeability, hardness, and many other physical and mineralogical rock properties (Al Saud, 2018).

Many classifications were followed on rock lithologies according to terrain instability, such the classification done by Church (1983), Hungr (1984) and Chatwin, et al. (1994). However, these properties are different according to rock characteristics with respect to the movement in the terrain surface. This can be attributed to the different characteristics of areas where these classification were applied. In this study, the classification of lithology-terrain instability (5-classes categorization) was obtained as lithological categorization for lithologies that match similar impact on terrain instability (Table 7.4).

The classified lithologies were mapped to illustrate their geographic distribution and their respond to terrain instability and mass movement (Fig. 7.5). A systematic

Table 7.4 Lithological classes according to terrain instability in Jeddah-Rabigh Region

Class	Major lithology	Area (km^2)	%	Terrain stability**
I	Alluvial and colluvial deposits, dunes, Sabkha, aeolian deposits	6049	30.5	Moveable
II	Conglomerate, sand, silt, tuff, marl, clay, argillaceous rocks	2386	12	Instable
III	Lava and volcanic ash, limestone	5532	28	Non-compacted
IV	Amphibole, ultramafic rocks, tonalite,	2735	14	Slightly stable
V	Basalt, rhyolite, andesite, granite, quartzite, gabbro, gneiss, Syenite	3021	15.5	Very stable

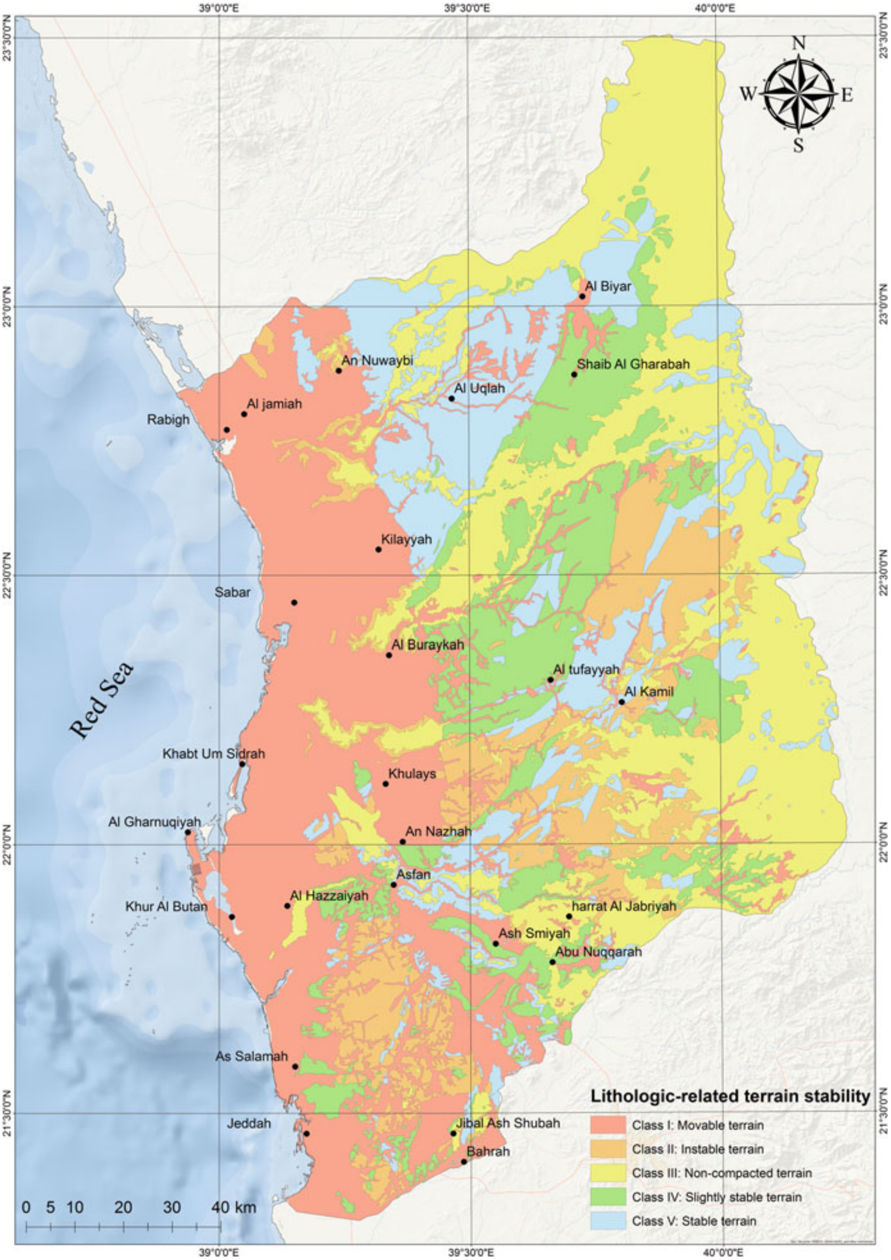

Fig. 7.5 Lithology-terrain instability map of Jeddah-Rabigh Region. (Al Saud, 2018)

lithological merging was followed for the lithologies with similar impact on terrain instability, whether these lithologies are attributed to the same rock formation or not.

7.3.3 Fractures

Large-scale fractures (e.g. faults) and significant factors in terrain instability. These are represented by large alignments of rock deformations. These faults resulted largely in creating other (secondary) fractures such as fissures and joints. Whereas, fissures and joints often exist in very local exposure and it could not be well identified in large-scale areal assessment.

Identification of large-scale fault alignments is successfully obtained by using satellite images, which enable identifying linear geological features on these images, the so-called “Lineaments”. Therefore, space techniques are good tools for the identification of linear features as observed on satellite images. They appear to be tremendous on hard rock bodies and negligible on soft terrain (Al Saud, 2008).

Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) satellite images were processed in this study. Aster L1A Reconstructed Unprocessed Instrument Data V003. ASTER is an advanced multi-spectral sensor with electromagnetic spectral region ranges from visible to thermal infrared, and it occupies 14 spectral bands. The spatial resolution of these images is 15 m with a visible bands, while they have 60 km x 60 km swath width, and thus 15 image scenes were used to cover the entire study area.

ERDAS Imagine-11, and PCI’s Geomatica-10.2 software were used for image processing. These types of software encompass several digital advantages for image processing. Therefore, a number of steps have been followed starting by the preprocessing step with a series of consequent operations, including mainly: 1) atmospheric correction or normalization, image registration, geometric and radiometric corrections; 2) linking of the required image scenes, which is also called “Images Mosaicking”. This is necessary in order to obtain a unique scene from all images required to cover the entire area of interest, and to facilitate further image treatment approaches.

Lineament identification from satellite images depends mainly on the thermal differentiation where thermal anomalies are the target features to be identified. These features represent the linear alignment of the existing fractures. These fractures, with dominant soil and detrital sediments and thus higher water retention (i.e. wetness) than the surrounding, will show cooler temperature than the rest terrain body.

Thermal bands (i.e. band number 10–14) in ASTER images, as attributed to Thermal Infrared (TIR), were processed. They are characterized by 90 m spatial resolution. In addition to the use of TIR bands, other spectral and digital advantage on ASTER images were utilized such as: color slicing and contouring, filtering, edge detection, band combination, enhancement, etc. Consequently, the lineament map was produced for the area between Jeddah and Rabigh.

There are 3189 lineaments detected in the area of study where they have different lengths. Many of the identified lineaments exist for long distance exceeding several tens of kilometers, while small-length lineaments also exist and they were found as geographic clusters.

The identified linear features are unevenly distributed in the study area, and thus their density was different between different localities. Therefore, a density map for lineaments is necessary to illustrate their concentration. In this regard, areas with dense lineaments (fractures) are characterized weak terrain stability and vice versa (Greenbaum, 1985; Al Saud, 2008).

The density of Lineaments can be elaborated using several approaches, but the most creditable one is that accounts the total number of lineaments with as specific area (geographic frame with known area). This concept is also followed by many researchers such as Gustafsson (1994) and Teeuw (1995). Hence lineaments density ($\mathrm{L_D}$) can be expressed by the following equation:

$$\mathrm{L_D} = \frac{\sum \mathrm{Ln}}{\mathrm{A}}$$

Where Σ Ln is the total number of lineaments, and A the define area where the counted lineament located in. In this study a lineament density map was produced with five classes (Fig. 7.6 and Table 7.5).

The generation of this map followed Sliding Windows approach, in which the area of study was classified into frames of 5 km x 5 km, and then the number of lineament was counted in each frame. Consequently, the resulting numeric values were again plotted in the middle of each frame. The resulting values were used once more to build up the contours map using Arc-GIS software (Fig. 7.6).

The average lineament density for the area between Jeddah and Rabigh was calculated as 4 lineaments per 25 km^2 (Al Saud, 2018). The description of the five classes of lineaments density was illustrated in Table 7.5.

7.3.4 Landforms

The influence of landform on terrain instability and mass movement implies several elements, with a special emphasis to the rigidity of terrain materials and structure. Hence, these physical characteristic are often deduced from the obtained landform maps. In this study, landforms were adopted from the Land Resources Maps of Kingdom of Saudi Arabia, which was obtained by the Ministry of Agriculture and Water (1986). For the area between Jeddah and Rabigh, there are 13 landform. The landforms with almost similar impact on terrain instability were digitally combined, using Arc-GIS, and then categorize into 5 classes (Fig. 7.7 and Table 7.6).

The obtained landforms map shows that 30% of the region between Jeddah and Rabigh is characterized suitability terrain instability.

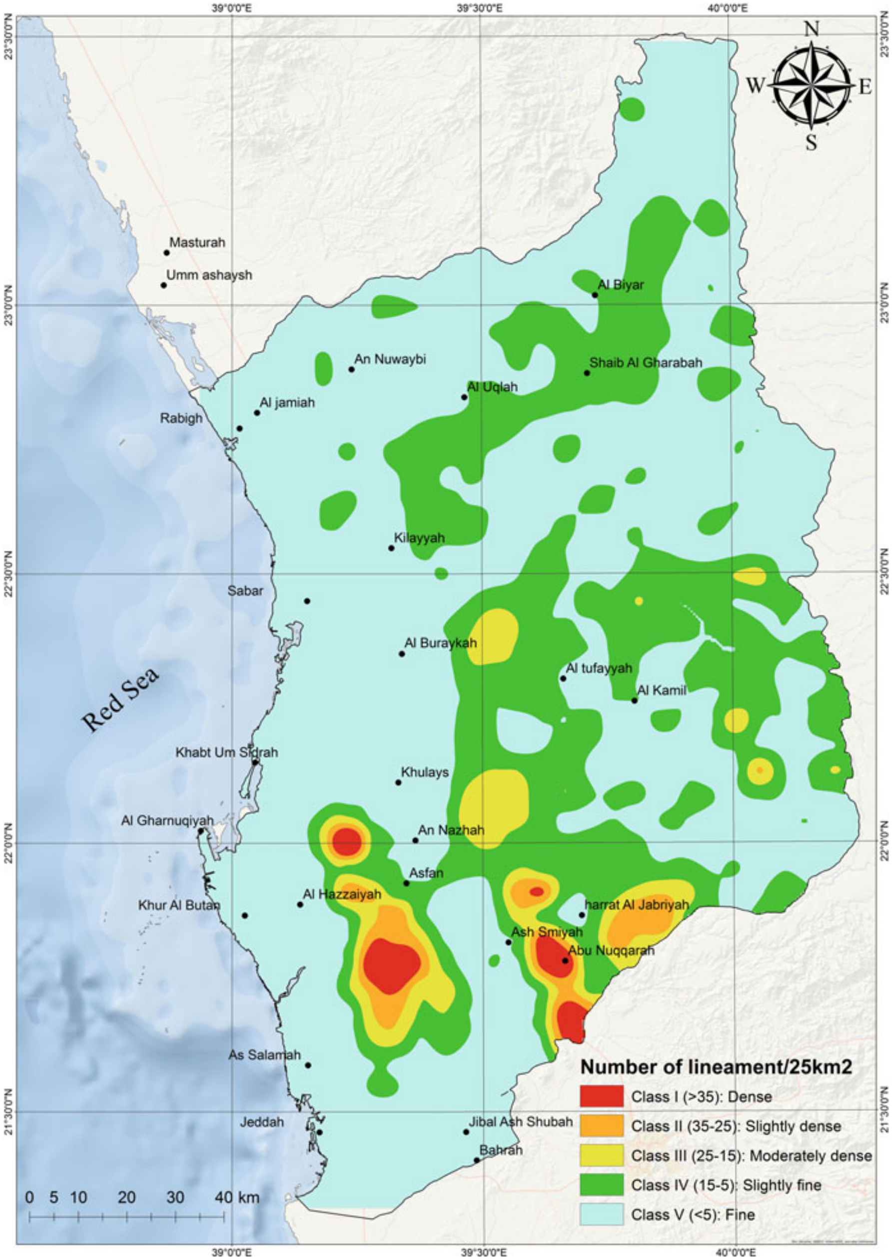

Fig. 7.6 Lineaments density map of Jeddah-Rabigh Region. (Al Saud, 2018)

Table 7.5 Classification of lineaments density in Jeddah-Rabigh Region

Class	Lineament density (lineaments/25km^2)	Description	Terrain instability
I	>35	Dense	Moveable
II	35–25	Slightly dense	Instable
III	25–15	Moderately dense	Non-compacted
IV	15–5	Slightly fine	Slightly stable
V	<5	Fine	Very stable

7.4 Data Manipulation

The geospatial data for the main influencing factors on terrain instability were identified and digitally illustrated using Arc-GIS. The GIS layers of the influencing data were plotted with their 5 classes for each. In order to create a map for the terrain instability in the area of interest; therefore, all these factors must be integrated together in one digital unit. In other word, all identified factors and their elements must act together to localize the geographic areas with different characteristics towards terrain instability (i.e. hotspots). Nevertheless, not all these factor have the same impact on the existence of terrain instability. Hence, some factors have larger influencing than others, and this must be considered during the digital manipulation of these factors together. Therefore, each factor must be attributed to specific degree of impact, which has been described as “weight”.

For example, the impact of landforms aspect on terrain stability is not similar as that of fractures, and so on for the rest factors and their elements. The determined weights of each factors and the belonging elements will be used during data integration in the Arc-GIS.

The following steps must be followed for data manipulation:

1. Factors to be prepared as digital maps, and each factor will be considered as a GIS layer with five classes (elements).
2. The obtained classes will be ordered from the highest to lowest impact. Thus, Class I must represent the most effective (i.e. unstable) terrain instability to Class V as the lowest impact (i.e. very stable). Also, there will be a defining for the weights of influence for each factor.
3. Producing the digital maps of all factors after considering their weights. This can be done using ESRI‘s Arc-GIS (i.e. Arc-View) software by “superimposing” different GIS layers together in the GIS system.
4. Each weight will attributed to a numeric percentage value, where the total for all factors must be 100%.
5. The five classes of each factor have also specific impact on terrain instability. For example, Class I in slope factor differs from Class I in lithology factor. Therefore, a “rate” has been dedicated for each class.

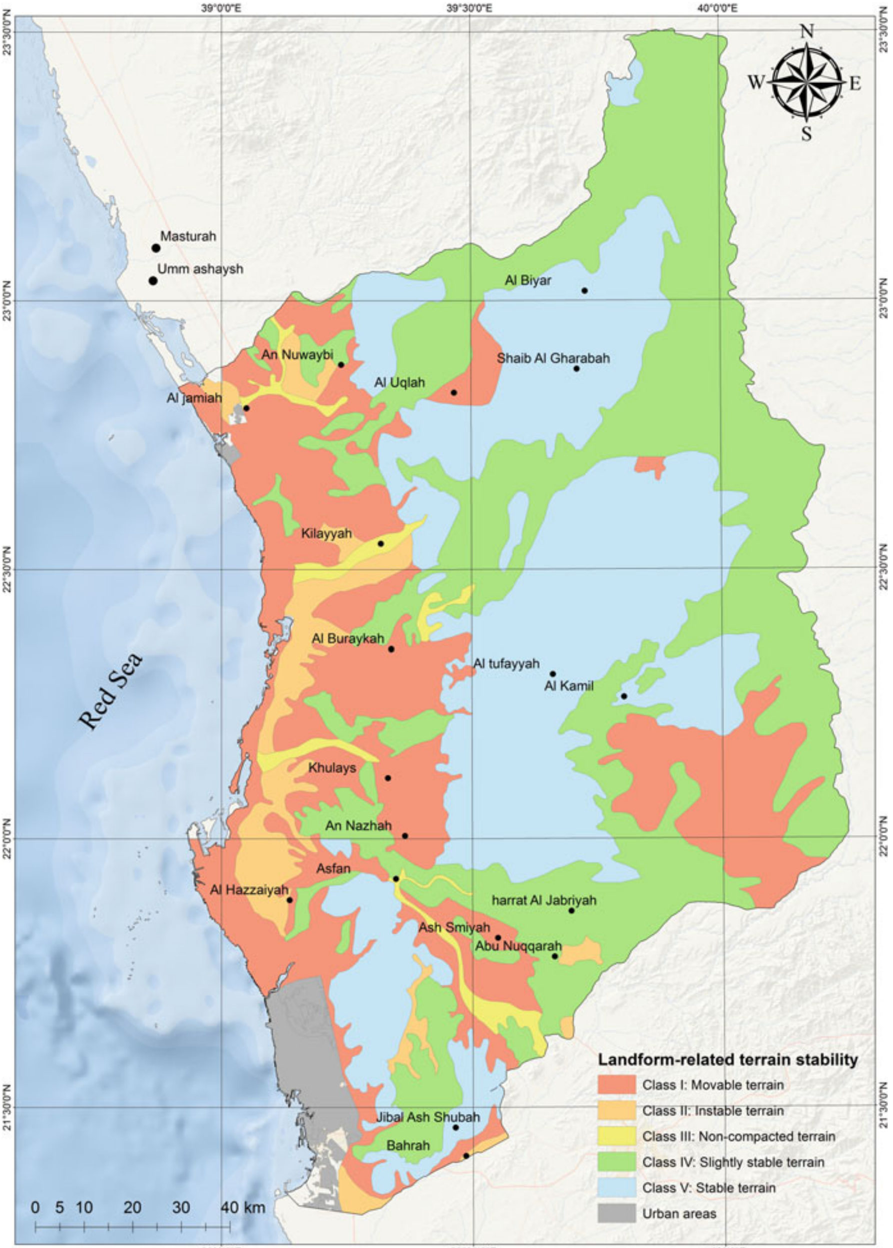

Fig. 7.7 Landform-terrain instability map of Jeddah-Rabigh Region. (Al Saud, 2018)

Table 7.6 Landform classes according to terrain instability in Jeddah-Rabigh Region

Class	Land form aspect	Area (km^2)	%	Terrain instability
I	Coastal plain, tidal flats, alluvial fans and foot slopes, degraded plain/active slopes	4750	24	Moveable
II	Alluvial plain, Pediplan with deep soils	983	5	Instable
III	Pediplan with shallow soils, Wadi deposits	461	2.5	Non-compacted
IV	Hills and rock outcrops, lava fields and volcanic hills	7180	36.5	Slightly stable
V	Mountains	6349	32	Very stable

The adoption of values for weights and rates were determined based on the following, according to Al Saud (2018):

1. Field experience and observations in field studies and the related ground investigations.
2. The assessment of the impact of factors depended on by many studies obtained by Edet et al. (1998); Robinson, et al. 1999); Das (2000) and Shaban et al. (2006).

Based on the above points and considering Al Saud (2010), the adopted factors in this study were given the following weights: slope (35%), lithology (30%), fractures (20%) and landform (15%). Table 7.7 shows weights of factor (F_w) and rate (F_r) and Effectiveness (E_f) for the influencing factors on terrain instability.

Rates are accounted with 100 as the maximum value 0 for the minimum value, thus, rates of the five classes will illustrated as follows: 100–80, 80–60, 60–40, 40–20 and 20–0. Therefore, the average of rating for each class will be 90, 70, 50, 30 and 10 for classes from I to V; respectively (Table 7.7).

To calculate the degree of effectiveness (E_f) for each factor depending on weight (F_w) and rate (F_r). Hence, each weight will be multiplied by the rate (F_w x F_r). For example, the weight of lithology is 30%, if multiplied by class II of the rate, which is 70%; therefore, the degree of effectiveness will be as follows:

$$E_f = F_w \times F_r = 30/100 \times 70 = 21$$

The sum of effectiveness for all classes will be 250 as shown in Table 7.8. Therefore, for each class the net effectiveness (En) is calculated by dividing the factor effectiveness (E_f) on the Sum of effectiveness, which equals 250 (Table 7.8). For example, E_n for Class II in the lithology was calculated as follows: $E_n = E_f /\sum$ effectiveness $= 21/250$ x $100 = 8.4\%$.

The E_n for each classes will be digitally converted in the GIS system, and they will represent the elements of the systematic integration of factors in order to produce the terrain instability map.

Table 7.7 Weights and rates of effectiveness on terrain stability (Al Saud, 2018)

Class/Factor	I	II	III	IV	V	
Slope (°)						
$\mathbf{F_w}$	35%					
$\mathbf{F_r}$	90	70	50	30	10	
$\mathbf{E_f}$	31.5	24.5	17.5	10.5	3.5	87.5
Lithology						
$\mathbf{F_w}$	30%					
$\mathbf{F_r}$	90	70	50	30	10	
$\mathbf{E_f}$	27	21	15	9	3	75
Fractures (lineament/25km^2)						
$\mathbf{F_w}$	20%					
$\mathbf{F_r}$	90	70	50	30	10	
$\mathbf{E_f}$	18	14	10	6	2	50
Landform						
$\mathbf{F_w}$	15%					
$\mathbf{F_r}$	90	70	50	30	10	
$\mathbf{E_f}$	13.5	10.5	7.5	4.5	1.5	37.5
Sum of effectiveness						**250**

Table 7.8 Net effectiveness of classes composing influencing factors in terrain instability (Al Saud, 2018)

Class/Factor	I	II	III	IV	V
Slope					
$\mathbf{E_n}$	12.6	9.8	7	4.2	1.4
Lithology					
$\mathbf{E_n}$	10.8	8.4	6	3.6	1.2
Fractures					
$\mathbf{E_n}$	7.2	5.6	4	2.4	0.8
Landforms					
$\mathbf{E_n}$	5.4	4.2	3	1.8	0.6

7.5 Results

The obtained map, with five main categories, evidences the degree of influence on terrain instability and the related mass movements (Fig. 7.8).

This maps shows about 90% of the area between Jeddah and Rabigh is under risk of terrain instability (ranges from high to very high risk). Therefore, from the obtained map, the following dimensions were calculated using GIS application:

- Very high risk (movable) = 8308 km^2 (42% of the studies area).
- High risk (instable) = 9383 km^2 (48% of the studies area).
- Moderate risk (non-compacted) = 1118 km^2 (6% of the studies area).
- Low risk (slightly stable) = 568 km^2 (2.5% of the studies area)
- No risk (very stable) = 346 km^2 (1.5% of the studies area).

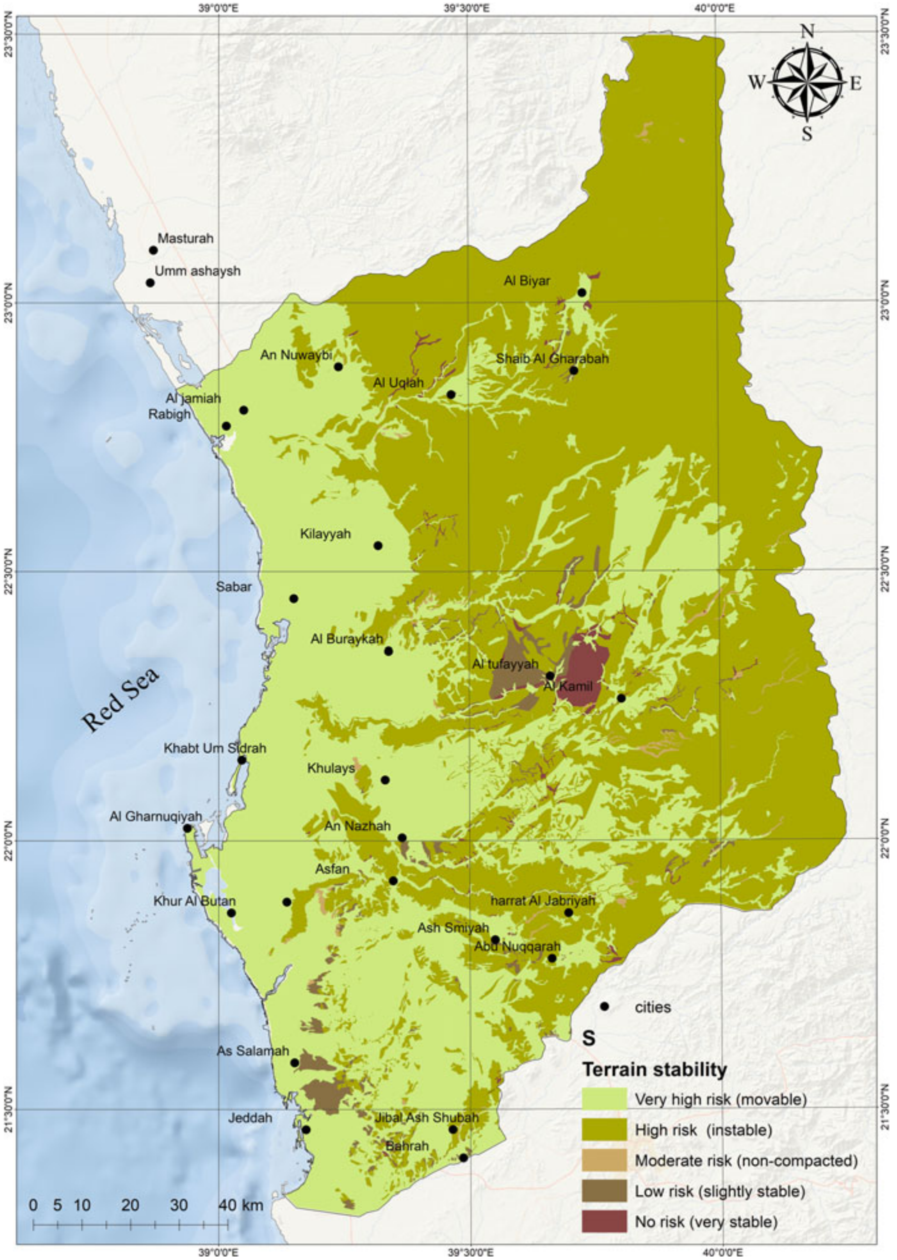

Fig. 7.8 Terrain stability map of Jeddah-Rabigh Region. (Al Saud, 2018)

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